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MULTIJET PRODUCTION AND DOUBLE PARTON SCATTERING AT TEVATRON

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Abstract

We report the differential cross-section for events with large total transverse energies, based on 112 pb^{-1} $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV. The ratio of number of 3-jet to 2-jet events as a function of total transverse energy is also presented. Obtained results are compared with the QCD expectations. The properties of high mass six-jet events have been studied. Observed distributions are compared with the predictions of HERWIG parton shower QCD, NJETS matrix element QCD, and a phase-space model in which events are uniformly distributed in the kinematic allowed region of phase space.

A strong signal for Double Parton Scattering (DP) is observed in the process $\bar{p}p \rightarrow \gamma + 3jets + X$, using data from the CDF experiment. The fundamental DP parameter σ_{eff} obtained, $\sigma_{eff} = 14.5 \pm 1.7^{+1.7}_{-2.3}$ mb, represents a significant improvement over previous measurements.

1 ΣE_T Differential Cross-Section

Within the frame work of perturbative QCD, events with large total transverse energy are expected to be produced in $\bar{p}p$ collisions from $2 \rightarrow 2$ hard scattering. Higher-order corrections give rise to additional jets in the final state. Therefore, the study the rate and properties of multijet events, forms additional tests of QCD, in addition to the traditional inclusive jet and dijet analyses.

The data used in this ΣE_T analysis were recorded by the CDF experiment with a trigger requirement, $\Sigma E_T^{cluster} > 175$ GeV, and correspond to an integrated luminosity of 112 ± 8 pb^{-1}. Jets are reconstructed using a cone algorithm with radius $R \equiv (\Delta\eta^2 + \Delta\phi^2)^{1/2} = 0.7$. The measured ΣE_T spectrum was corrected for smearing effects caused by the finite experimental E_T^{jet} resolutions. The unsmeared ΣE_T differential cross-section is compared with the predictions from NLO QCD (JETRAD [1]) and from LO QCD (HERWIG [2]), using the scale $\mu = 0.5\Sigma E_T^{jet}$ and $Q^2 = stu/2(s^2 + t^2 + u^2)$, respectively.

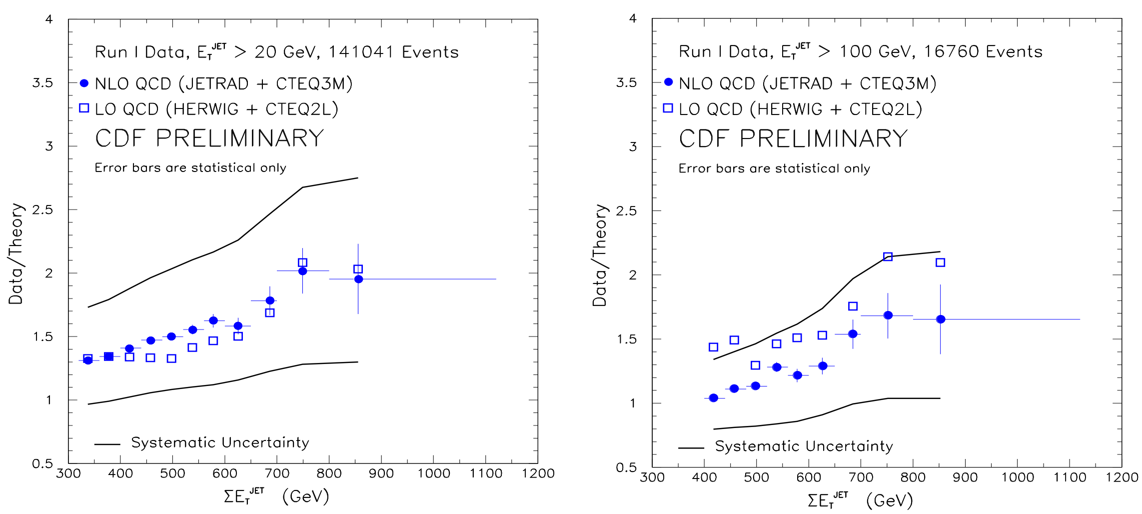

Figure 1: The unsmeared ΣE_T cross-section divided by LO and NLO QCD (data/theory) for (a) $E_T^{jet} > 20$ GeV and (b) $E_T^{jet} > 100$ GeV.

Figure 1 shows the ratio of ΣE_T spectra between data and LO/NLO QCD for $E_T^{jet} > 20$ GeV and $E_T^{jet} > 100$ GeV. For $E_T^{jet} > 20$ GeV, data are around 45% higher than the NLO QCD prediction and around 33% higher than the HERWIG prediction at $\Sigma E_T = 320 - 480$ GeV. The discrepancy between data and the NLO QCD prediction indicates that NLO $2 \rightarrow 2$ calculation is not adequate to predict the event rate at large ΣE_T. Note that we observe more three jet events than two jet events in our $\Sigma E_T > 320$ GeV data sample with the requirement, $E_T^{jet} > 20$ GeV. When we raise the jet E_T cut to 100 GeV, there is only 1% difference between data and the NLO prediction at low ΣE_T region, suggesting that NLO $2 \rightarrow 2$ calculation can better describe the data once we are in the region where 2-jet events dominate. The HERWIG prediction is still 39% higher than the data even for $E_T^{jet} > 100$ GeV, which can be explained by a K factor difference bewteen the LO calculation and the data. However, there is an obvious rising trend in these ratio plots, which indicates that the observed spectra are harder than NLO QCD and HERWIG predictions at $\Sigma E_T > 500$ GeV. This effect is similar to the one seen in the CDF inclusive jet cross-section [3].

2 Three Jet to Two Jet Ratio

Another way to test QCD is to measure the event rate for inclusive three jet production to two jet production and compare to NLO predictions. Figure 2 shows the measured ratio as a function of H_T ($H_T = \Sigma E_T$) for E_T threshold of 20 and 30 GeV from the D0 collaboration. The theoretical prediction was obtained by Summers and Zepenfeld [4], who used a version of JETRAD with MRSD_' parton distribution functions and the scale $\mu_R = H_T/4$ for the leading two jets. Two different renormalization scales for the third jet were used in the calculation: $\mu_R^3 = H_T/4$ and $\mu_R^3 = E_T^3$, where E_T^3 is the transverse energy of the third jet. Reasonable agreement between data and theory is seen for both E_T threshold requirements. The data corresponding to 30 GeV, however, prefers the softer renormalization scale for the third jet. Various systematic studies are underway.

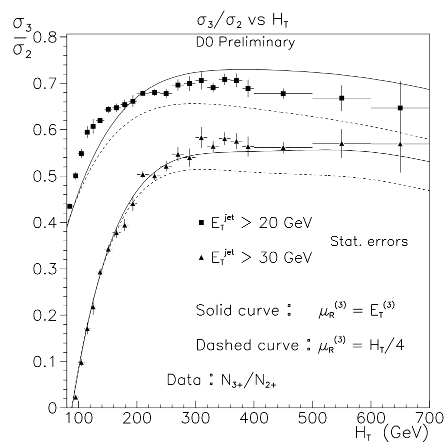

Figure 2: The production ratio of inclusive three jet to two jet events as a function of H_T for data and NLO QCD predictions.

3 Properties of Six-jet events

In this section, we report the characteristics of six-jet events with six-jet mass $m_{6j} > 520$ GeV/c^2. Observed distributions are compared to the predictions from the HERWIG QCD program, the NJETS QCD calculation, and a phase-space model. This comparison provides an interesting test of the approximations used in HERWIG and NJETS QCD calculations.

This analysis uses the same data sample as described in Section 1. To select events with six or more jets, we require at least six well separated jets ($\Delta R > 0.9$) reconstructed with the cone algorithm (cone size 0.7) with $E_T > 20$ GeV and jet pseudorapidity $|\eta| < 3$. Besides,

$\Sigma E_T > 320$ GeV is required to restrict our analysis to the region where trigger was fully efficient. In our HERWIG calculations we used the CTEQ2L parton distribution functions and the scale $Q^2 = stu/2(s^2 + t^2 + u^2)$, while in NJETS program we used CTEQ3L parton distribution functions and the scale $Q^2 =< P_T^2 >$.

In a N-jet system, we need (4N - 4) variables to fully describe this N-jet properties in the N-jet rest frame [6]. Therefore, twenty six-jet variables are introduced as defined in Reference [5]. The first variable we choose is the six_jet mass, m_{6j}. To define the remaining 19 variables, we begin reducing the six-jet system to a five-body system by merging two objects with the lowest two-body mass. Applying the same technique, we further reduce a five-body system to a four-body system and then to a three-body system by merging two objects. Hence, three merging steps have been taken. In the three-body system we choose the traditional three-jet variables (7 variables) as described in Ref. [6]. In each merged two-body system, four extra variables are needed. Total 19 variables plus m_{6j} are thus defined.

In general, both HERWIG QCD and NJETS QCD give a good description of the observed distributions although some distributions are not completely matched with data. Figure 3 shows the three-body angular distributions ($\cos\theta_{3'''}$ and $\psi_{3'''}$) for data, HERWIG predictions, NJETS calculations, and phase-space expectations. In these angular distributions, events for data and both QCD Monte Carlo programs are more populated at $|\cos\theta_{3'''}|$ near to 1 and $\psi_{3'''}$ near 0 or π, reflecting the shape of the leading order QCD $2 \rightarrow 2$ scattering and the preference of QCD matrix element for planar topologies. Both QCD programs give a reasonable description of the $\cos\theta_{3'''}$ and $\psi_{3'''}$ distributions except that HERWIG predictions slightly underestimate the event rate at $\psi_{3'''} = 0$ or π. This feature has also been observed in the previous 3-jet, 4-jet, and 5-jet analysis [7].

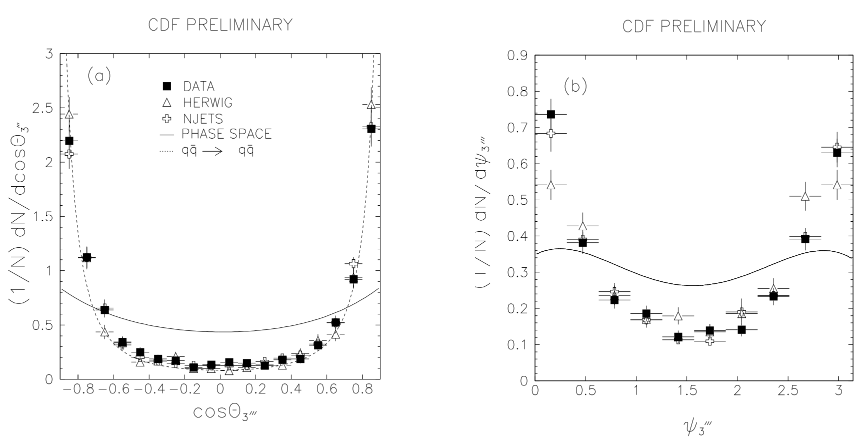

Figure 3: The three-body angular distributions, $\cos\theta_{3'''}$ and $\psi_{3'''}$, for data, HERWIG, NJETS, and phase-space predictions. $\cos\theta_{3'''}$ is the cosine value of the angle between the highest $E_T$object and the average beam direction and $\psi_{3'''}$ is the angle bewteen the plan which contains the two softer objects and the plane spanned by the highest E_T object and the average beam direction.

Fig. 4 shows the distributions of the two-body sharing variable X_j, where $X_j = \frac{E_j}{E_j+E_i}$, $E_j > E_i$. Both QCD predictions favor a more asymmetric energy sharing than the phase-space model, reflecting the soft gluon radiation pole in the QCD matrix element. The NJETS predictions overestimate the event rate at large X_j region, which is the region that a lot of soft gluon corrections need to be applied. The HERWIG program performs the soft gluon resummations; therefore, it is expected that the HERWIG QCD gives a better description than the NJETS QCD does. In comparing all 20 observed distributions, we conclude that $2 \to 2$ scattering plus initial and final-state gluon radiation provides a good approximation in describing the six-jet kinematics.

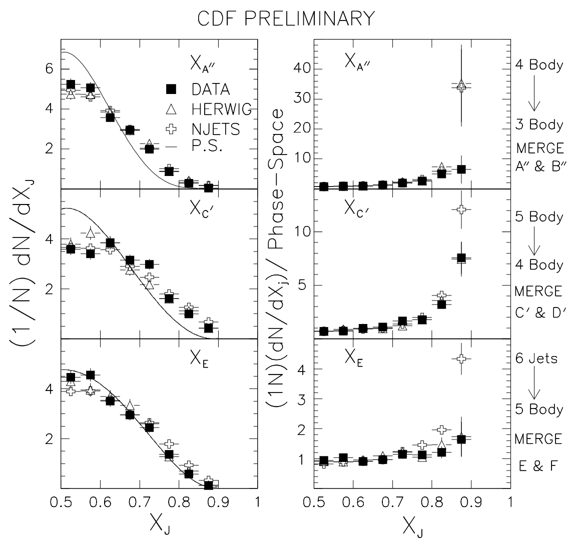

Figure 4: The two-body energy sharing distributions.

4 Double-Parton Scattering

The Double-Parton-Scattering (DP) process provides information on the spatial distributions of partons within protons and on possible parton-parton correlations. It is customary to express the DP cross-section as the following form:

$$\sigma_{DP} = \frac{\sigma_A \times \sigma_B}{\sigma_{eff}}, \tag{1}$$

where σ_A and σ_B are cross-sections for single scatterings A and B. The above equation is under two assumptions: number of parton-parton interactions per collision is distributed with Poisson statistics and two scatterings, A and B, are distinguishable. The previous best measurement of $\sigma_{eff} = 12.1^{+10.7}_{-5.4}$ mb, was obtained from the 1989 CDF [8] analysis of four-jet events with $P_T^{jet} > 25$ GeV/c. Currently, the D0 experiment is searching DP in a 4-jet sample by using a neural network. This work is still in progress. However, the CDF experiment has observed a strong DP signal using $\gamma + 3$ jet data, which have permitted an investigation of kinematic correlations between the two scatterings. The detail analysis is documented in Ref. [9].

This analysis used an inclusive photon trigger with $E_T > 16$ GeV, corresponding to an integrated luminosity of 16 pb^{-1}. Jet reconstruction was performed using a cone algorithm (cone size 0.7). Events with three and only three jets with $E_T > 5$ GeV (uncorrected) were accepted. A further requirement of $E_T < 7$ GeV was made on the two lowest E_T jets. Events with single VTX vertex were taken as DP candidates. No jet rapidity requirement was applied.

A set of six variables was defined to distinguish DP events from DP candidates. The variable with greatest sensitivity, ΔS taken in Ref. [8], is the azimuthal angle between the P_T vectors of the two best-balancing pairs (photon + 1 jet and dijet). In QCD events, momentum conservation biases ΔS toward 180^0, while in the DP events the ΔS distribution should be flatter. Fig. 5 shows the ΔS distribution, indicating that 52.6$\pm$2.5% of DP candidates are from double scatterings. The effective cross-section is determined to be $\sigma_{eff} = 14.5 \pm 1.7^{+1.7}_{-2.3}$ mb.

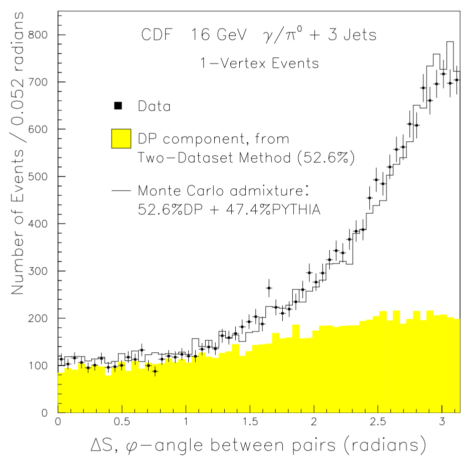

Figure 5: Distribution of the ΔS variable. The DP component to the data, determined by the two-dataset method (see Ref. 8) to be 52.6% of the sample, is shown as the shaded region. The admixture of DP and QCD (Pythia) Monte Carlo is also shown.

The possible Feynman x dependence of σ_{eff} was studied by searching for the deviations between data and the Monte Carlo model in which two scatterings were not correlated. To further enrich the DP events from our data, we applied an extra cut, $\Delta S < 1.2$. The data passing this cut should be 90% DP events. Each event was subdivided into two best-balance pairs and four x values were calculated. We then compared these x distributions with the predictions from the admixture of 90% DP MC model and 10% Pythia (single scattering only). Figure 6 shows the comparisons. No distinct differences is found, suggesting that σ_{eff} is not x dependent.

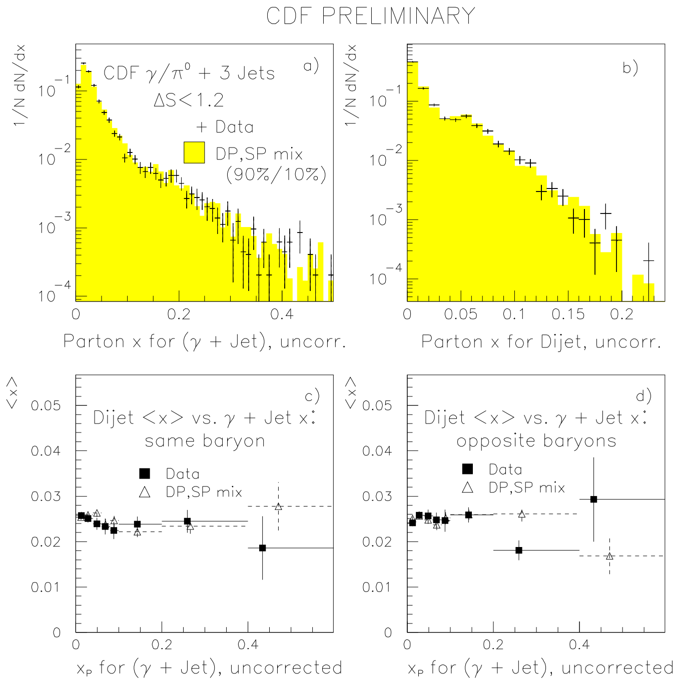

Figure 6: Results of Feynman x analysis. Distributions of (a) x in $\gamma+1$ jet system, (b) x in dijet system, (c) the average dijet x versus the x in $\gamma+1$ jet system for the same baryon, and (d) the average dijet x in $\gamma+1$ jet system for the opposite baryons.

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